

# INTERNATIONAL STANDARD

# NORME INTERNATIONALE



**Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems –  
Part 2: Modular multilevel converters**

**Pertes de puissance dans les valves à convertisseur de source de tension (VSC)  
des systèmes en courant continu à haute tension (CCHT) –  
Partie 2: Convertisseurs multiniveaux modulaires**



## THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2023 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Secretariat  
3, rue de Varembe  
CH-1211 Geneva 20  
Switzerland

Tel.: +41 22 919 02 11  
[info@iec.ch](mailto:info@iec.ch)  
[www.iec.ch](http://www.iec.ch)

### About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

### About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

#### IEC publications search - [webstore.iec.ch/advsearchform](http://webstore.iec.ch/advsearchform)

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

#### IEC Just Published - [webstore.iec.ch/justpublished](http://webstore.iec.ch/justpublished)

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

#### IEC Customer Service Centre - [webstore.iec.ch/csc](http://webstore.iec.ch/csc)

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: [sales@iec.ch](mailto:sales@iec.ch).

#### IEC Products & Services Portal - [products.iec.ch](http://products.iec.ch)

Discover our powerful search engine and read freely all the publications previews. With a subscription you will always have access to up to date content tailored to your needs.

#### Electropedia - [www.electropedia.org](http://www.electropedia.org)

The world's leading online dictionary on electrotechnology, containing more than 22 300 terminological entries in English and French, with equivalent terms in 19 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

### A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

### A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

#### Recherche de publications IEC -

##### [webstore.iec.ch/advsearchform](http://webstore.iec.ch/advsearchform)

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études, ...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

#### IEC Just Published - [webstore.iec.ch/justpublished](http://webstore.iec.ch/justpublished)

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

#### Service Clients - [webstore.iec.ch/csc](http://webstore.iec.ch/csc)

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: [sales@iec.ch](mailto:sales@iec.ch).

#### IEC Products & Services Portal - [products.iec.ch](http://products.iec.ch)

Découvrez notre puissant moteur de recherche et consultez gratuitement tous les aperçus des publications. Avec un abonnement, vous aurez toujours accès à un contenu à jour adapté à vos besoins.

#### Electropedia - [www.electropedia.org](http://www.electropedia.org)

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 300 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 19 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.



IEC 62751-2

Edition 1.2 2023-08  
CONSOLIDATED VERSION

# INTERNATIONAL STANDARD

# NORME INTERNATIONALE



**Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems –  
Part 2: Modular multilevel converters**

**Pertes de puissance dans les valves à convertisseur de source de tension (VSC) des systèmes en courant continu à haute tension (CCHT) –  
Partie 2: Convertisseurs multiniveaux modulaires**

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

COMMISSION  
ELECTROTECHNIQUE  
INTERNATIONALE

ICS 29.200, 29.240.99

ISBN 978-2-8322-7472-9

**Warning! Make sure that you obtained this publication from an authorized distributor.  
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**



# REDLINE VERSION

## VERSION REDLINE



**Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems –  
Part 2: Modular multilevel converters**

**Pertes de puissance dans les valves à convertisseur de source de tension (VSC)  
des systèmes en courant continu à haute tension (CCHT) –  
Partie 2: Convertisseurs multiniveaux modulaires**

## CONTENTS

FOREWORD.....	5
1 Scope.....	7
2 Normative references .....	7
3 Terms, definitions, symbols and abbreviated terms.....	7
3.1 Terms and definitions.....	8
3.2 Symbols and abbreviated terms .....	9
3.2.1 Valve and simulation data.....	9
3.2.2 Semiconductor device characteristics .....	10
3.2.3 Other component characteristics.....	10
3.2.4 Operating parameters .....	10
3.2.5 Loss parameters .....	11
4 General conditions.....	11
4.1 General.....	11
4.2 Principles for loss determination .....	12
4.3 Categories of valve losses .....	12
4.4 Loss calculation method.....	13
4.5 Input parameters.....	13
4.5.1 General .....	13
4.5.2 Input data for numerical simulations .....	13
4.5.3 Input data coming from numerical simulations .....	15
4.5.4 Converter station data .....	15
4.5.5 Operating conditions.....	16
4.6 Contents and structure of valve loss determination report .....	16
5 Conduction losses .....	16
5.1 General.....	16
5.2 IGBT conduction losses .....	18
5.3 Diode conduction losses .....	19
5.4 Other conduction losses.....	20
6 DC voltage-dependent losses .....	21
7 Losses in d.c. capacitors of the valve .....	21
8 Switching losses .....	22
8.1 General.....	22
8.2 IGBT switching losses.....	22
8.3 Diode switching losses.....	23
9 Other losses .....	23
9.1 Snubber circuit losses.....	23
9.2 Valve electronics power consumption.....	24
9.2.1 General .....	24
9.2.2 Power supply from off-state voltage across each IGBT .....	25
9.2.3 Power supply from the d.c. capacitor .....	25
10 Total valve losses per HVDC substation .....	26
Annex A (informative) Description of power loss mechanisms in MMC valves .....	28
A.1 Introduction to MMC Converter topology .....	28
A.2 Valve voltage and current stresses .....	31
A.2.1 Simplified analysis with voltage and current in phase.....	31
A.2.2 Generalised analysis with voltage and current out of phase .....	32

A.2.3	Effects of third harmonic injection .....	33
A.3	Conduction losses in MMC building blocks .....	34
A.3.1	Description of conduction paths .....	34
A.3.2	Conduction losses in semiconductors .....	40
A.3.3	MMC building block d.c. capacitor losses .....	44
A.3.4	Other conduction losses .....	45
A.4	Switching losses .....	45
A.4.1	Description of state changes .....	45
A.4.2	Analysis of state changes during cycle .....	46
A.4.3	Worked example of switching losses .....	47
A.5	Other losses .....	50
A.5.1	Snubber losses .....	50
A.5.2	DC voltage-dependent losses .....	50
A.5.3	Valve electronics power consumption .....	53
A.6	Application to other variants of valve .....	55
A.6.1	General .....	55
A.6.2	Two-level full-bridge MMC building block .....	55
A.6.3	Multi-level MMC building blocks .....	56
Annex B (informative)	Recommended data to be supplied with the loss calculation report .....	58
Annex C (informative)	Loss measurement .....	60
Bibliography	.....	61
Figure 1	– Two basic versions of MMC building block designs .....	16
Figure 2	– Conduction paths in MMC building blocks .....	17
Figure A.1	– Phase unit of the modular multi-level converter (MMC) in basic half-bridge, two-level arrangement, with submodules .....	29
Figure A.2	– Phase unit of the cascaded two-level converter (CTL) in half-bridge form .....	30
Figure A.3	– Basic operation of the MMC converters .....	31
Figure A.4	– MMC converters showing composition of valve current .....	32
Figure A.5	– Phasor diagram showing a.c. system voltage, converter a.c. voltage and converter a.c. current .....	33
Figure A.6	– Effect of 3 <sup>rd</sup> harmonic injection on converter voltage and current .....	34
Figure A.7	– Two functionally equivalent variants of a “half-bridge”, two-level MMC building block .....	35
Figure A.8	– Conducting states in “half-bridge”, two-level MMC building block .....	36
Figure A.9	– Typical patterns of conduction for inverter operation (left) and rectifier operation (right), based on the submodule configuration of Figure A.7 a) .....	37
Figure A.10	– Example of converter with only one MMC building block per valve to illustrate switching behaviour .....	38
Figure A.11	– Inverter operation example of switching events .....	38
Figure A.12	– Rectifier operation example of switching events .....	39
Figure A.13	– Valve current and mean rectified valve current .....	41
Figure A.14	– IGBT and diode switching energy as a function of collector current .....	46
Figure A.15	– Valve voltage, current and switching behaviour for a hypothetical MMC valve consisting of 5 submodules .....	48
Figure A.16	– Power supply from IGBT terminals .....	53

Figure A.17 – Power supply from IGBT terminals in cell .....	54
Figure A.18 – Power supply from d.c. capacitor in submodule .....	55
Figure A.19 – One “full-bridge”, two-level MMC building block .....	56
Figure A.20 – Four possible variants of three-level MMC building block .....	57
Table 1 – Contributions to valve losses in different operating modes .....	27
Table A.1 – Hard switching events .....	45
Table A.2 – Soft switching events .....	46
Table A.3 – Summary of switching events from Figure A.15 .....	49
Table B.1 – Valve loss data .....	58
Table B.2 – Other data .....	59

iTeh STANDARD PREVIEW  
(standards.iteh.ai)

[IEC 62751-2:2014](https://standards.iteh.ai/catalog/standards/sist/02524bb0-191e-43c3-b209-aad7aea76431/iec-62751-2-2014)

<https://standards.iteh.ai/catalog/standards/sist/02524bb0-191e-43c3-b209-aad7aea76431/iec-62751-2-2014>



## INTERNATIONAL ELECTROTECHNICAL COMMISSION

---

# POWER LOSSES IN VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –

## Part 2: Modular multilevel converters

### FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

**This consolidated version of the official IEC Standard and its amendments has been prepared for user convenience.**

**IEC 62751-2 edition 1.2 contains the first edition (2014-08) [documents 22F/303/CDV and 22F/322A/RVC], its amendment 1 (2019-08) [documents 22F/479/CDV and 22F/488B/RVC] and its amendment 2 (2023-08) [documents 22F/712/CDV and 22F/726/RVC].**

**In this Redline version, a vertical line in the margin shows where the technical content is modified by amendments 1 and 2. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.**

International Standard IEC 62751-2 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62751series, published under the general title *Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems*, can be found on the IEC website.

The committee has decided that the contents of this document and its amendments will remain unchanged until the stability date indicated on the IEC website under [webstore.iec.ch](http://webstore.iec.ch) in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

**IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.**

[IEC 62751-2:2014](https://standards.iteh.ai/catalog/standards/sist/02524bb0-191e-43c3-b209-aad7aea76431/iec-62751-2-2014)

<https://standards.iteh.ai/catalog/standards/sist/02524bb0-191e-43c3-b209-aad7aea76431/iec-62751-2-2014>

# POWER LOSSES IN VOLTAGE SOURCED CONVERTER (VSC) VALVES FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS –

## Part 2: Modular multilevel converters

### 1 Scope

This part of IEC 62751 gives the detailed method to be adopted for calculating the power losses in the valves for an HVDC system based on the “modular multi-level converter”, where each valve in the converter consists of a number of self-contained, two-terminal controllable voltage sources connected in series. It is applicable both for the cases where each modular cell uses only a single turn-off semiconductor device in each switch position, and the case where each switch position consists of a number of turn-off semiconductor devices in series (topology also referred to as “cascaded two-level converter”). The main formulae are given for the two-level “half-bridge” configuration but guidance is also given in Annex A as to how to extend the results to certain other types of MMC building block configuration.

The standard is written mainly for insulated gate bipolar transistors (IGBTs) but may also be used for guidance in the event that other types of turn-off semiconductor devices are used.

Power losses in other items of equipment in the HVDC station, apart from the converter valves, are excluded from the scope of this standard.

This standard does not apply to converter valves for line-commutated converter HVDC systems.

<https://standards.iteh.ai/catalog/standards/sist/02524bb0-191e-43c3-b209-aad7aea76431/iec-62751-2-2014>

### 2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60633, *Terminology for high-voltage direct-current (HVDC) transmission*

IEC 61803, *Determination of power losses in high-voltage direct current (HVDC) converter stations*

IEC 62747, *Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems*

IEC 62751-1:2014, *Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems – Part 1: General requirements*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

### 3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in IEC 60633, IEC 62747, IEC 62751-1, as well as the following apply.

### 3.1 Terms and definitions

#### 3.1.1

##### **modular multi-level converter**

##### **MMC**

multi-level converter in which each VSC valve consists of a number of MMC building blocks connected in series

Note 1 to entry: This note applies to the French language only.

#### 3.1.2

##### **MMC building block**

self-contained, two-terminal controllable voltage source together with d.c. capacitor(s) and immediate auxiliaries, forming part of a MMC

#### 3.1.3

##### **IGBT-diode pair**

arrangement of IGBT and free-wheeling diode connected in inverse parallel

#### 3.1.4

##### **switch position**

semiconductor function which behaves as a single, indivisible switch

Note 1 to entry: A switch position may consist of a single IGBT-diode pair or, in the case of the cascaded two level converter, a series connection of multiple IGBT-diode pairs.

#### 3.1.5

##### **cascaded two-level converter**

##### **CTL**

modular multi-level converter in which each switch position consists of more than one IGBT-diode pair connected in series

Note 1 to entry: This note applies to the French language only.

#### 3.1.6

##### **submodule**

MMC building block where each switch position consists of only one IGBT-diode pair

#### 3.1.7

##### **cell**

MMC building block where each switch position consists of more than one IGBT-diode pair connected in series

#### 3.1.8

##### **turn-off semiconductor device**

controllable semiconductor device which may be turned on and off by a control signal, for example an IGBT

#### 3.1.9

##### **insulated gate bipolar transistor**

##### **IGBT**

turn-off semiconductor device with three terminals: a gate terminal (G) and two load terminals emitter (E) and collector (C)

Note 1 to entry: This note applies to the French language only.

#### 3.1.10

##### **operating state**

condition in which the HVDC substation is energized and the converters are de-blocked

Note 1 to entry: Unlike line-commutated converter, VSC can operate with zero active/reactive power output.

### 3.1.11

#### no-load operating state

condition in which the HVDC substation is energized but the IGBTs are blocked and all necessary substation service loads and auxiliary equipment are connected

Note 1 to entry: In the no-load state, in principle no switching should occur as the valve is blocked. However, in some designs, it may be necessary to make occasional switching operations to balance voltages between different parts of the converter. Here, some losses may occur and need to be accounted for. The integration time over which such losses are averaged might need to be longer than during normal operation, so as to obtain the correct weighted average of the losses while blocked and the losses while switching.

### 3.1.12

#### idling operating state

condition in which the HVDC substation is energized and the IGBTs are de-blocked but with no active or reactive power output at the point of common connection to the a.c. network

Note 1 to entry: The “idling operating” and “no-load” conditions are similar but from the no-load state, several seconds may be needed before power can be transmitted, while from the idling operating state, power transmission may be commenced almost immediately (less than 3 power frequency cycles).

Note 2 to entry: In the idling operating state, the converter is capable of actively controlling the d.c. voltage, in contrast to the no-load state where the behavior of the converter is essentially “passive”.

Note 3 to entry: Losses will generally be slightly lower in the no-load state than in the idling operating state, therefore this operating mode is preferred where the arrangement of the VSC system permits it.

### 3.1.13

#### modulation index of PWM converters

$M$

ratio of the peak line to ground a.c. converter voltage, to half of the converter d.c. terminal to terminal voltage

IEC 62751-2:2014

$$M = \frac{\sqrt{2} \cdot U_{c1}}{\sqrt{3} \cdot \frac{U_{dc}}{2}}$$

where

$U_{c1}$  is the r.m.s value of the fundamental frequency component of the line-to-line voltage  $U_c$ ;

$U_c$  is the output voltage of one VSC phase unit at its a.c. terminal;

$U_{dc}$  is the output voltage of one VSC phase unit at its d.c. terminals.

Note 1 to entry: Some sources define modulation index in a different way such that a modulation index of 1 refers to a square-wave output, which means that the modulation index can never exceed 1. The modulation index according to that definition is given simply by  $M \cdot (\pi/4)$ . However, that definition is relevant mainly to two-level converters using PWM.

## 3.2 Symbols and abbreviated terms

### 3.2.1 Valve and simulation data

$N_{tc}$  number of MMC building blocks per valve

$N_c$  number of series-connected semiconductor devices per switch position

$N_{sr}$  total number of series resistive elements contributing to conduction losses in the valve, other than in the IGBTs and diodes

$N_{cv}$  number of d.c. capacitors in the valve

$N_s$  number of switching cycles (on or off) experienced by each VSC valve level during the integration time  $t_i$

$N_{pr}$  total number of parallel resistive elements contributing to d.c. voltage dependent losses in the valve

$N_{\text{sn}}$	number of snubber circuits per valve
$t_i$	integration time used in the simulation

### 3.2.2 Semiconductor device characteristics

$V_{0T}$	average IGBT threshold voltage for the relevant operating conditions
$R_{0T}$	average IGBT slope resistance for the relevant operating conditions, valid at the device terminals
$V_{0D}$	average diode threshold voltage for the relevant operating conditions
$R_{0D}$	average diode slope resistance for the relevant operating condition, valid at the device terminals
$E_{\text{on}}$	average turn-on energy dissipated in the IGBT for the relevant operating conditions
$E_{\text{off}}$	average turn-off energy dissipated in the IGBT(s) for the relevant operating conditions
$E_{\text{on},T1\_j,k}$	turn-on energy dissipated in IGBT T1 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ turn-on event for the relevant operating conditions (voltage, current and junction temperature)
$E_{\text{on},T2\_j,k}$	turn-on energy dissipated in IGBT T2 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ turn-on event for the relevant operating conditions (voltage, current and junction temperature)
$E_{\text{off},T1\_j,k}$	turn-off energy dissipated in IGBT T1 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ turn-off event for the relevant operating conditions (voltage, current and junction temperature)
$E_{\text{off},T2\_j,k}$	turn-off energy dissipated in IGBT T2 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ turn-off event for the relevant operating conditions (voltage, current and junction temperature)
$E_{\text{rec},D1\_j,k}$	diode recovery energy dissipated in diode D1 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ diode turn-off event for the relevant operating conditions (voltage, current and junction temperature)
$E_{\text{rec},D2\_j,k}$	diode recovery energy dissipated in diode D2 in the $j^{\text{th}}$ MMC building block for the $k^{\text{th}}$ diode turn-off event for the relevant operating conditions (voltage, current and junction temperature)

### 3.2.3 Other component characteristics

$R_{s\_k}$	total resistance of the $k^{\text{th}}$ series resistive elements in the valve contributing to other conduction losses
$R_{\text{dc}_k}$	resistance of the $k^{\text{th}}$ parallel resistive component in the valve
$R_{\text{ESR}_j}$	average equivalent series resistance of the $j^{\text{th}}$ d.c. capacitor
$E_{\text{sn,on}_j,k}$	energy dissipated in the snubber resistor of the $j^{\text{th}}$ snubber circuit for the $k^{\text{th}}$ turn-on event for the relevant operating conditions (voltage, and current where relevant to the design of the snubber)
$E_{\text{sn,off}_j,k}$	energy dissipated in the snubber resistor of the $j^{\text{th}}$ snubber circuit for the $k^{\text{th}}$ turn-off event for the relevant operating conditions (voltage, and current where relevant to the design of the snubber)

### 3.2.4 Operating parameters

$I_{T1\text{av}_j}$	mean current of IGBT T1 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{T2\text{av}_j}$	mean current of IGBT T2 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{T1\text{rms}_j}$	rms current of IGBT T1 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$

$I_{T2rms\_j}$	rms current of IGBT T2 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{D1av\_j}$	mean current of diode D1 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{D2av\_j}$	mean current of diode D2 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{D1rms\_j}$	rms current of diode D1 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{D2rms\_j}$	rms current of diode D2 in the $j^{\text{th}}$ MMC building block, averaged over an integration time $t_i$
$I_{rms\_k}$	rms current flowing in the $k^{\text{th}}$ series resistive element for the relevant operating conditions
$U_{rms\_k}$	rms value (including d.c. component) of the voltage across the $k^{\text{th}}$ parallel resistive component in the valve
$I_{crms\_j}$	rms current flowing in the $j^{\text{th}}$ d.c. capacitor of the valve
$P_{GU\_j,k}$	average power input to the power supply of $k^{\text{th}}$ IGBT in $j^{\text{th}}$ MMC building block
$P_{GU\_j,k}(t)$	instantaneous power input to the power supply of $k^{\text{th}}$ IGBT in $j^{\text{th}}$ MMC building block
$u_{GU\_j,k}(t)$	instantaneous voltage input to the power supply of $k^{\text{th}}$ IGBT in $j^{\text{th}}$ MMC building block
$i_{GU\_j,k}(t)$	instantaneous current input to the power supply of $k^{\text{th}}$ IGBT in $j^{\text{th}}$ MMC building block
$P_{GU\_j}$	average power input to the power supply in $j^{\text{th}}$ MMC building block
$P_{GU\_j}(t)$	instantaneous power input to the power supply in $j^{\text{th}}$ MMC building block
$u_{GU\_j}(t)$	instantaneous voltage input to the power supply in $j^{\text{th}}$ MMC building block
$i_{GU\_j}(t)$	instantaneous current input to the power supply in $j^{\text{th}}$ MMC building block

### 3.2.5 Loss parameters

$P_{V1}$	IGBT conduction losses
$P_{V2}$	diode conduction losses
$P_{V3}$	other valve conduction losses
$P_{V4}$	d.c. voltage-dependent losses
$P_{V5}$	d.c. capacitor losses
$P_{V6}$	IGBT switching losses
$P_{V7}$	diode turn-off losses
$P_{V8}$	snubber losses
$P_{V9}$	valve electronics power consumption
$P_{Vt}$	total valve losses

## 4 General conditions

### 4.1 General

Modular multi-level converters (MMC) are a family of converters in which each valve forms a controllable voltage source. The converter a.c. voltage is synthesized by switching large numbers of relatively small, self-contained, two-terminal controllable voltage sources at different times, thereby obtaining a high-quality converter waveform with low switching losses and therefore a high overall efficiency. The MMC building blocks from which the overall converter is built up may use multiple IGBT-diode pairs connected in series (in which case the converter is referred to as the “Cascaded two level converter”, CTLC) or only a single IGBT-